HERRO Missions to Mars and Venus using Telerobotic Surface Exploration from Orbit

George R. Schmidt,[1] Geoffrey A. Landis,[2] and Steven R. Oleson[3]
NASA Glenn Research Center, Cleveland, Ohio, 44135

This paper presents concepts for human missions to the orbits of Mars and Venus that feature direct robotic exploration of the planets' surfaces via teleoperation from orbit. These missions are good examples of Human Exploration using Real-time Robotic Operations (HERRO), an exploration strategy that refrains from sending humans to the surfaces of planets with large gravity wells. HERRO avoids the need for complex and expensive man-rated lander/ascent vehicles and surface systems. Additionally, the humans are close enough to the surface to eliminate the two-way communication latency that constrains typical robotic space missions, thus allowing real-time command and control of surface operations and experiments by the crew. In fact through use of state-of-the-art telecommunications and robotics, HERRO could provide the cognitive and decision-making advantages of having humans at the site of study for only a fraction of the cost of conventional human surface missions. HERRO is very similar to how oceanographers and oil companies use telerobotic submersibles to work in inaccessible areas of the ocean, and represents a more expedient, near-term step prior to landing humans on Mars and other large planetary bodies. Its concentration on in-space transportation systems makes it extensible to destinations that have not been associated with human missions in the past but may be of potentially great scientific interest, such as Venus.

I. Introduction

IN a previous paper, we outlined a strategy for human exploration that combines elements of both human spaceflight and robotic exploration in a cost-effective strategy for exploration that could be adapted to multiple targets in the solar system.[1,2] This Human Exploration using Real-time Robotic Operations (HERRO)[1] approach differs from the traditional view of human exploration, in that it does not land humans on planetary surfaces within large gravity wells. It instead envisions piloted spacecraft sent on missions that orbit, rather than land on, planetary targets. The crew then explores the surface via teleoperation of robotic vehicles deployed on the surface.

HERRO provides the cognitive and decision-making advantages of having humans at the site of study by allowing real-time command and control of operations and experiments. With the humans in a nearby vehicle, and hence engaging in teleoperation in nearly real-time operation, HERRO realizes most of the advantages of direct human engagement via a virtual human presence on the planet with substantially less flight hardware and risk.[3] The strategy is not intended to replace human presence on the surface, but rather to present an incremental pathway, developing the in-space transportation systems and many of the technologies needed for eventual human landings.[4]

This paper presents two concepts that would utilize the HERRO approach. One is a mission to Mars in which the orbiting crew would perform extensive telerobotic exploration of the surface over a period of approximately 1-1/2 year.[5] The other is a mission to Venus, which would use many of the flight systems developed for the Mars mission.[6]

It is assumed that one or more HERRO-Mars missions would take place first. After this, the exploration path could lead to one or more of the following scenarios:
- Continue telerobotic-based exploration of Mars by crew in orbit;
- Use the infrastructure to establish a base or long-term crew-tended outpost on Phobos or Deimos;
- Proceed with human landed missions using the in-space infrastructure developed for HERRO-Mars;
- Apply the infrastructure to conduct HERRO missions to new destinations.

---

[1] Deputy Director, Research and Technology, MS 3-5, AIAA Senior Member.
[2] Scientist, Photovoltaics and Power Technologies Branch, MS 302-1, AIAA Associate Fellow.
[3] Lead Engineer, Systems Analysis Branch, MS 105-3, AIAA Senior Member.

Apart from Near Earth Objects (NEOs), the only other destination comparable to Mars in terms of mission velocity and mission duration is Venus. This planet has not been seriously considered as a destination for human exploration because its high temperature (450 °C) and pressure (90 bar) preclude landing astronauts on its surface. Studies during the Apollo era evaluated Venus as a target for human flyby and orbital missions,[7] but there has been no serious interest since that time. However, the HERRO strategy, with its emphasis on telerobotic exploration, and recent advances in high-temperature electronics[8] and power systems[9], could make Venus a prime candidate for a human orbital mission.

A key point is that HERRO-Venus could be performed with the same crew vehicle and support systems used for HERRO-Mars. Such a mission would be impractical if it required a unique set of crewed elements and systems. But if the systems are available then having human operations within the proximity of the surface could facilitate exploration over traditional approaches using autonomous robotic systems. Direct control of surface robots allows the simplification of their computational electronics, thus enabling use of simple and rugged electronics and control systems built from high-temperature, silicon-carbide materials that are currently under development [b]. This would cut cooling requirements dramatically and extend mission times from hours/days to months/years.

II. HERRO- Mars Mission

The HERRO-Mars mission architecture is similar to NASA's Design Reference Architecture (DRA) 5.0, which was completed in 2008 to assist exploration planning efforts.[10] The DRA 5.0 reference focuses on crewed missions to the Mars surface, and actually envisions three separate missions launched over a period of six years that explore three different regions on the surface. The area explored on each mission is limited to roughly a 50-km traverse from the landing site (100-km diameter area).

DRA 5.0 features split-sprint missions in which the cargo elements are sent out prior to the crew leaving Earth. For each mission, two cargo vehicles are first sent to Mars, each one assembled using two heavy-lift (130 metric ton (mT) heavy lift) launches to LEO. A Nuclear Thermal Rocket (NTR) propelled[11] Mars Transit Vehicle (MTV) is assembled in LEO over a series of three heavy-lift launches. A final launch of an Ares-I (or equivalent) human-launch vehicle delivers the crew capsule/service module with the six-person crew to the assembled MTV. The crew flies on a conjunction-class trajectory to Mars, and stays on the Martian surface for approximately 500 days in the pre-deployed cargo and habitat elements. Once surface operations are complete, the crew uses the ascent vehicle pre-deployed on the surface to return to the orbiting MTV, which then propels itself to a hyperbolic Earth return trajectory. The crew-return capsule returns directly to Earth, while the remaining MTV flies by. Each DRA 5.0 mission requires a total of seven heavy-lift (Ares-V or equivalent) launches, plus one launch of a six-person crew capsule/service module vehicle on a human-rated launch vehicle with the crew.[12-14]

The goal of the HERRO-Mars mission is to achieve a level of scientific exploration comparable to that of DRA 5.0 in terms of number of sites explored and the quality of the science gleaned at each site. The architecture features a Crew Telerobotic Center Vehicle (CTCV),[10] very similar to the MTV in DRA 5.0.[9] Surface exploration elements include three "Truck" rovers,[13] each of which supports two teleoperated geologist robots, called "Rockhounds."[14] Each of the three Truck/Rockhound groups is launched separately on an Atlas-V or Delta-IV, and is pre-deployed on Mars using an aeroshell-based lander system. Another element that could be included is a sample-return system to bring selected rock and soil samples back to the CTCV, but such a capability was not considered in this study.

Each Truck/Rover group would land in a science location with the ability to traverse a 100-kilometer diameter area. Each Truck would carry the Rockhounds to multiple locations for science activities lasting up to several weeks. The truck is not only responsible for transporting the Rockhounds to these areas, but also for relaying telecontrol and high-resolution communications to/from the Rockhounds and powering/heating the Rockhounds during night and periods of inactivity. The Rockhounds effectively substitute as human geologists by providing an agile robotic platform with real-time control from the crew in the CTCV.

The HERRO-Mars mission begins 2.2 years before launch of the crew, with deployment of the three Truck/Rover groups. These groups land using proven entry, descent and landing techniques at three different locations around the planet. After these groups are checked out and operational, the CTCV, which requires three heavy-lift (Ares-V or equivalent) launches for assembly and one human crew launch for crew transport, departs Earth and follows a conjunction-class trajectory to Mars. Once it captures into a highly elliptical 12-hr Molniya-like Mars orbit, the CTCV beings to spin at 2.7 rpm to provide Mars g-level artificial gravity. After the astronauts have acclimatized, they begin to operate the Trucks and Rockhounds.

The mission duration entails nearly 500 days in Mars orbit. Once the surface exploration phase of the mission is finished, the CTVC despins and begins the return to Earth using an NTR burn. Final return of the crew is performed

using the Orion vehicle on a hyperbolic trajectory. After the Orion vehicle has been jettisoned, the CTCV flies by Earth. Sufficient ΔV reserves are kept to return the CTCV to the Earth-Moon Lagrange point (L1), where it can be stored and refueled for use in future missions. A total of seven launches are needed to complete each mission.

A. HERRO-Mars Orbit

Communications between the CTCV and the ground science sites could be done either by a direct link or with one or more satellite relays. The relay option increases the flexibility of the choice of orbits, but has the disadvantage of greater complexity, added failure modes, and a larger number of elements. Thus, the study assumed a direct link, and an orbit that provides a direct view of the surface during telerobotic operations.

Lester and Thronson[15] define the cognitive horizon for teleoperation in space, that is, "how distant can an operator be from a robot and not be significantly impacted by latency," in terms of the round-trip delay time. They note that this can be as low as 100 milliseconds for full haptic (touch) control, and that at about 200 milliseconds the delays become noticeable in visual feedback applications. They conclude that, "with sophisticated telepresence, there is little obvious value for humans to be closer to a target site than light can travel in ~100 ms: human perception and response is typically not much faster than this." This corresponds to a distance of 30,000 km, which represents the maximum altitude sufficient for highly effective teleoperation.

Studies of human factors have shown that astronaut fatigue results in poor performance as well as degraded judgment when work shifts exceed roughly eight hours per day over extended periods. Thus, this study assumes no more than eight-hour operation shifts at each site.

Additional considerations for orbit selection include:
- Allow selection of surface sites at multiple locations, including both high- and low-latitudes.
- Constrain telerobotic operations to occur during sunlight.
- Minimize the required ΔV for orbital insertion and for trans-Earth injection.
- Minimize ground-to-orbit distance primarily to reduce power required for high-bandwidth communications.

The final HERRO-Mars orbit is shown in Fig. 1. It has a 12-hour and 20 minute period (*i.e.*, 12 Mars hours, or exactly half a Sol (Mars day)), and is inclined 116° in a nearly-sun-synchronous Molniya-type orbit.[10] The apoapsis on the sunlit side occurs twice per Sol, but the planet rotates under the orbit such that a site on the opposite side of the planet is seen each time. With this orbit, two 8-hour shifts of scientist/teleoperators can explore sites on each side of Mars during each Sol.
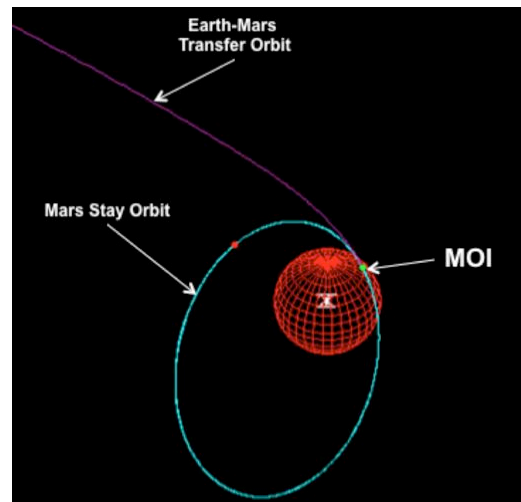

Figure 1. HERRO-Mars 12-hour elliptical orbit.

B. HERRO-Mars CTCV

The CTCV provides the crew with an orbital habitat and platform to operate the Trucks and Rockhounds, as well as a means for transporting crew to and from Mars orbit. An important design requirement is to protect the crew from space radiation and the prolonged microgravity environment. To address these challenges, the design includes both water shielding for radiation and vehicle spinup/spindown to provide a centrifugal force to mitigate the effect of microgravity.

The design concept is shown in Fig. 2. The vehicle is adapted from the MTV in DRA 5.0, which uses nuclear thermal propulsion and an inflatable TransHab-based crew habitat.[11]

The CTCV is divided into four elements. Each element is launched separately and integrated with other elements in LEO to form the assembled vehicle. These consist of the following, in order of launch from Earth:
- Habitat Element: Contains the crew quarters and all the components necessary to provide a safe haven for the crew.
- Drop Tank Element: Contains the hydrogen propellant to perform the first Trans-Mars Injection (TMI) burn. Once the TMI 1 is performed, the tank is dropped, leaving the saddle truss structure behind.
- In-Line Tank Element: Contains much of the propellant for TMI 2 and Mars Orbit Capture (MOC).

- Core Element: Contains the NTR engines and reactors along with the structure and tankage to carry the propellant for Trans-Earth Injection (TEI).
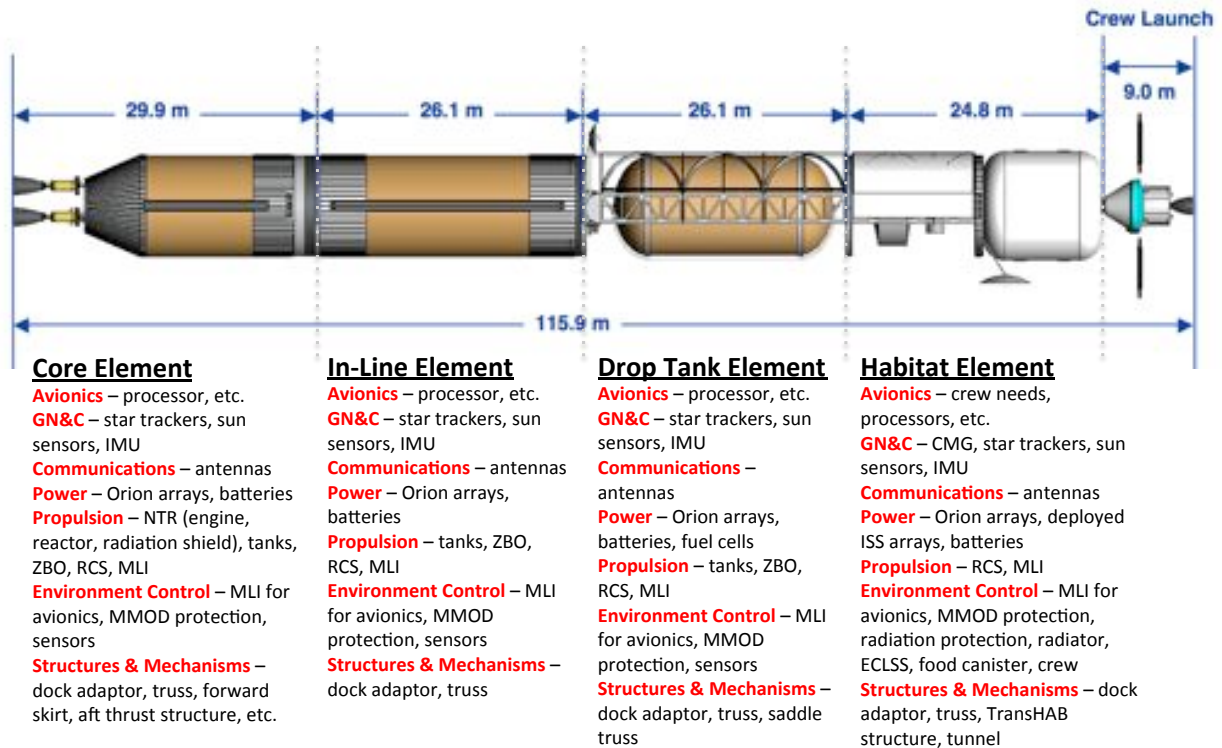

Core Element
Avionics – processor, etc.
GN&C – star trackers, sun sensors, IMU
Communications – antennas
Power – Orion arrays, batteries
Propulsion – NTR (engine, reactor, radiation shield), tanks, ZBO, RCS, MLI
Environment Control – MLI for avionics, MMOD protection, sensors
Structures & Mechanisms – dock adaptor, truss, forward skirt, aft thrust structure, etc.

In-Line Element
Avionics – processor, etc.
GN&C – star trackers, sun sensors, IMU
Communications – antennas
Power – Orion arrays, batteries
Propulsion – tanks, ZBO, RCS, MLI
Environment Control – MLI for avionics, MMOD protection, sensors
Structures & Mechanisms – dock adaptor, truss

Drop Tank Element
Avionics – processor, etc.
GN&C – star trackers, sun sensors, IMU
Communications – antennas
Power – Orion arrays, batteries, fuel cells
Propulsion – tanks, ZBO, RCS, MLI
Environment Control – MLI for avionics, MMOD protection, sensors
Structures & Mechanisms – dock adaptor, truss, saddle truss

Habitat Element
Avionics – crew needs, processors, etc.
GN&C – CMG, star trackers, sun sensors, IMU
Communications – antennas
Power – Orion arrays, deployed ISS arrays, batteries
Propulsion – RCS, MLI
Environment Control – MLI for avionics, MMOD protection, radiation protection, radiator, ECLSS, food canister, crew
Structures & Mechanisms – dock adaptor, truss, TransHAB structure, tunnel

Figure 2: Crew Telerobotics Control Vehicle (CTCV)

In addition to the high data rates to provide control and High Definition Television (HDTV) video from the rovers, the CTCV employs radiation shielding to ensure crew health. The radiation protection comes from water (14 tonnes) strategically surrounding only the sleeping and working areas of the vehicle where 2/3 of the crews' day is spent. This approach saves over 30 tonnes of water shielding that would be needed for the entire TransHab. Other radiation protection options include hydrogenated plastic materials, use of hydrogen propellant to protect the crew, and implementation of electromagnetic shields.

Crew health issues due to microgravity can be significant on a ~900-day mission if the full time were spent in microgravity. Therefore, artificial gravity was assumed for all mission phases except during main engine firings. A Mars gravity level of 0.38 g, which is roughly midway between Earth and microgravity levels, was selected. It was assumed that this would be sufficient to maintain bone and muscle tone with the inclusion of a fitness regimen. The environment is created by spinning the CTCV at 2.7 rpm during the 500-day Mars stay. A higher level of effective gravity could be achieved with higher spin rates, but at the cost of larger Coriolis forces and other structural and dynamical complications. Other options that should be explored in future studies include small centrifuges and advanced exercise techniques.

C. HERRO-Mars Surface Operations

Unlike the DRA 5.0 reference, HERRO allows the possibility of exploring multiple regions in the same mission. Each HERRO mission will explore three widely-separated 100-km diameter science regions simultaneously.

Figure 3 shows how these regions are decomposed into areas of interest, which represent the endpoints for gross movement and transport of the Truck/Rockhound team in that region. The average separation distance between areas of interest was assumed to be 20 km, and each area is assumed to be approximately 1-km in diameter. In order to minimize time spent driving and to maximize time spent at each location, the 20-km journey should be accomplished in a single eight-hour shift. This requires that the Trucks be capable of a top speed of 1 m/s (3.6 km/hr).

Within each area of interest, there will be many individual science sites. These sites are the subject of detailed study with the Rockhound rovers, operated by geologists aboard the CTCV. Exploration of an area of interest will typically take place over a 2-week period. In a given area of interest, the rovers will stop at numerous science sites, which have areas of roughly 10-m diameter, the territory covered typically in one Sol.

Each science site is explored by two Rockhound rovers in a manner similar to how a team of geologists would conduct field research on Earth. By emulating human geologists working together in the field, the Rockhounds allow cooperative action by both geologists. They are designed to provide: agility, high definition video, and manipulation of samples (rock hammering and drilling). They must also be able to bring samples back for more complete X-ray and chemical analyses at the Truck or at the CTCV via a separately-deployed Mars ascent vehicle. Top speeds of 10 centimeters/second (cm/s) and climbing capabilities up to a 45° incline are baselined.

Figure 3. HERRO-Mars exploration areas.

Figure 4 shows the final Rockhound design developed in the study. The most significant mobility feature is the use of "whegs" (a wheel-leg that combines the function of a leg with the operation of a wheel) to improve rough-terrain mobility.[16] This biologically-inspired locomotion system can achieve good traction on rough terrain.[17]

The Rockhounds are designed to handle short distance mobility on rough terrain, including rocky scree, heaps of stones and rocky debris. The six titanium whegs, along with an articulating body joint, enables the Rockhound to traverse terrain at least 0.5-meters tall. The six whegs also enable operation, although degraded, in the event of a wheel failure. The body of the telerobot is articulated to allow the front section to lever upward to climb, while the four rear whegs provide stability and support. The Rockhound wheels are driven by individual motors, as well as the steering and body joints.

Figure 4. Rockhound telerobotic explorer.

The body of the Rockhound contains batteries and avionics, with the batteries in the rear to help center the mass of the overall vehicle. The estimated average power is roughly 200 watts (W) for the 8-hour teleoperation events. Power comes from a 1,200 watt-hour set of rechargeable batteries (50% depth of charge) with a small solar array (~20 W) added to the top deck of the Rockhound for contingency power.

The aluminum-framed body is between 0.5 to 1.0 meters long to promote stability. Navigation is provided by both LIDAR and navigational cameras located at each end of the vehicle. This allows steering control at both ends of the vehicle, and the ability to reverse out of tough locations. Thermal control is provided by foam insulation and small radiator panels, along with the option for radioisotope heater units (RHUs) for heating the motors and external instruments during nighttime storage.

The science instruments aboard each Rockhound include a Hyperspectral infrared (IR) camera, a Stereo HDTV camera and normal geologist's tools for manipulating rock samples. These are operated by a teleoperated human equivalent robot, equivalent to the Robonaut unit developed at NASA.[18] The telerobot on the Rockhound uses highly sensitive hands for manipulating the samples directly, and is controlled in real-time by astronauts in orbit. The ability to replace the hands with the science instruments/tools protects the hands for their main duties of collecting samples. Samples are stored in separate containers in the rear of the Rockhound.

The telerobot torso is designed to lean over the surface to allow coordinated visual and hand operations. The visual science is provided by stereo high resolution cameras set in the "head" of the telerobot. All communications are provided by a 1/2 watt radiated Wi-Fi type system with either a line-of-sight, 802.11 Wi-Fi antenna or a reflected 1-meter whip antenna. These provide the 20 Mbps data rate at a maximum distance of 100-meters with a healthy 30 db margin. The Rockhounds must be single fault tolerant and capable of operating for 18 months after landing two years earlier. Delivering the Rockhounds early ensures that systems are operational before the crew leaves Earth.
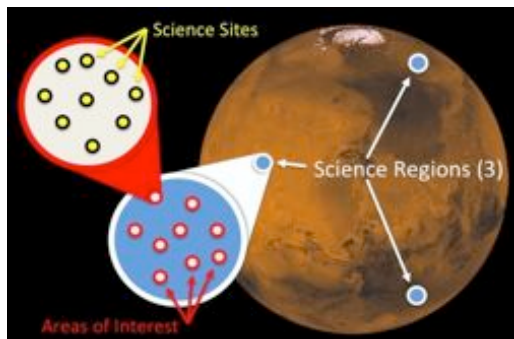
Environmental systems would need to address the possibility of dust storms and their impacts on the Rockhound performance.

The Truck, which is shown in Fig. 5, plays the same role as the astronauts' rover/habitat in the human landed mission. In addition to providing transport, laboratory and drilling functions, the Truck also functions as the charging station for the Rockhounds as well as a communications conduit with the CTCV. The Truck design uses a four-wheeled chassis with articulated control struts to raise and lower the vehicle with respect to the ground.

The truck design developed for this study can: charge up to 16 hrs in sunlight; handle high bandwidth surface-to-orbit communications; drive for 11 days to 34 different sites over the 500-day period; carry a science laboratory payload; and can perform science operations when not driving (i.e., operate science laboratory, drill, winch and cable, and surface-penetrating radar).

The Truck is designed to achieve a top speed of ~1 meter/second (m/s), with an average speed of 0.4 m/s and a range of several 100 km. It uses a standard four-wheel drive system, with each wheel independently operated by a separate motor. This gives the vehicle high ground clearance when needed to drive across rock-strewn plains, but allows the vehicle to lower down to the ground when the Rockhounds drive onto or off of the carrying platform. The articulation is also used to allow the vehicle to be folded up into the aeroshell for atmospheric entry. Finally, the vehicle body can be lowered to the ground to give a highly stable platform for operation of the drill to access the subsurface.

Figure 5. Truck with its complement of two Rockhound telerobots.

The truck mobility system is similar to that of the Nomad rover,[19] tested in operations in both desert environments and in Antarctica. The base of the Truck is roughly 2 meters by 2 meters, and the entire vehicle weighs slightly over 800 kilograms. A 4-meter diameter pointable Ultraflex solar array and Lithium-ion batteries provide power.
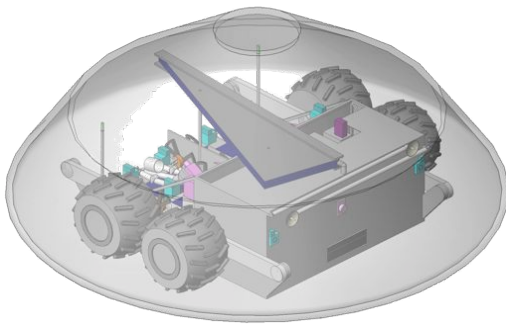

Figure 6. Truck shown stowed inside aeroshell for Mars entry and landing.

The Truck, with Rockhounds, is delivered to Mars using a larger cruise deck/aeroshell/sky crane based on the system that will be employed on the upcoming Mars Science Laboratory (MSL) mission in 2011. The vehicle is shown (with the Rockhounds) in Fig. 6 in its stowed configuration inside the lander aeroshell. The total mass of 3,565 kg is comfortably within the launch capability of an Atlas-V expendable launch vehicle for launch to the Mars-injection C_3 of 8.46 km^2/s^2.

III. HERRO- Mars Versus DRA 5.0

This study has shown the HERRO approach to be a highly cost-effective, science-oriented strategy for exploring the surface of Mars. A comparison between DRA 5.0 and HERRO-Mars is shown in Table 1.

Table 1: Comparison between DRA 5.0 (surface mission) and HERRO-Mars missions.

Criterion	DRA 5.0 Campaign	HERRO
Science Campaign: 3 x 100 km radius, widely separated regions	3 separate manned landed missions, landing in three locations, pre-position cargo one opportunity early	1 manned orbiting mission, telerobotically exploring three locations, pre-position telerobots one opportunity early
Location / Duration	Three 500 day stays, each at a 100 km radius region	Three 100 km radius regions, simultaneous telerobotic exploration
Launches (entire campaign)	21 Ares V + 6 Ares 1	4 Ares V, 2 Ares 1, 7 EELVs — 4 heavy lift + 2 Ares 1 + 3 rovers = 3 EELVs + 3 sample return to LMO = 3 EELVs + 1 sample rendezvous (LMO to Manned Vehicle)
Vehicle Elements (entire campaign)	3 Mars Transfer Vehicles, 6 Orion, 3 cargo lander, 3 cargo habitat ; 3 hab lander, 3 ascent vehicle, 3 habitat, 6 pressurized manned rovers, 6 unpressurized manned rovers (27 NTR engines)	1 Mars Transfer Vehicle, 3 telerobot truck carriers, 6 telerobot rockhounds, 3 sample ascent systems, 1 sample rendezvous system, (3 NTR engines)
Crew (entire campaign)	18, three crews of six	6, 4 geologists teleoperators (two shifts), two support
Technology development	Long duration crew on-orbit habitat, Cryofluid management and propellant transfer, Nuclear thermal rockets, Radiation protection, aerocapture (cargo) Landing descent, Landing ascent systems, Mars unique habitats/manned systems, Manned rovers, Surface suits, Surface reactor, In-situ propellant production for ascent system	Long duration crew on-orbit habitat, Cryofluid management and propellant transfer, Nuclear thermal rockets, Radiation protection, Artificial gravity, Telerobotics, Teleoperated rovers, Sample ascent system, Teleoperated sample rendezvous system

In terms of duration and surface area coverage, HERRO-Mars achieves approximately the same exploratory return as the entire DRA 5.0 campaign, which consists of three individual human-landed missions.

DRA 5.0 requires 27 separate launches, of which 21 are Ares V-class heavy lift vehicles. HERRO-Mars, on the other hand, requires 13 launches, of which only four are heavy lift. In fact, seven or almost half of the launches are performed with existing Atlas V or Delta IV-class vehicles.

The approaches also differ dramatically in the number of individual spacecraft and spaceflight elements required for the mission. DRA 5.0, which consists primarily of man-rated hardware, involves use of three MTVs, six Orion capsule/service modules, and three cargo landers, cargo habitats, habitat landers, ascent vehicles and habitats. Three pairs of pressurized rovers and unpressurized rovers are also required, in addition to 27 NTR engines.

HERRO-Mars requires only one CTCV (three NTR engines) and three Truck/Rockhound teams (i.e., three Trucks, six Rockhounds). Inclusion of sample-return capability would also require three sample-ascent systems and one system for orbital rendezvous and collection by the CTCV.

HERRO-Mars requires many of the same technologies needed for DRA 5.0. The main difference will be in crew health and habitation, which HERRO-Mars will entail longer duration exposure to microgravity and cosmic rays. However, it appears that a combination of new technology plus innovative design solutions (e.g., spinning CTCV to produce artificial gravity, water radiation protection) could readily address these issues.

IV. The Case for Phobos

An alternate possibility as a target for the HERRO-Mars teleoperation is to place the teleoperations base on Mars' moon Phobos. This location has been proposed by others. One advantage is that Phobos is in itself a target of some scientific interest. It is a small body with a reflectance spectrum and presumed composition similar to a type-C asteroid, but in a close orbit around a planet. Since it has only a very low gravity, access to the surface is comparatively simple, without the difficult engineering challenge of a Mars lander/ascent vehicle. As a base for operation of science telerobots on the Martian surface, it has both advantages and disadvantages. The distance from the Martian surface, about 6,000 km, is low enough that teleoperation could be accomplished with negligible speed-of-light delay. The most significant advantage is that Phobos itself will provide shielding against cosmic radiation from half of the sky, and Mars, viewed from Phobos, will block radiation about 7% from the remaining sky. Locating the teleoperation base in a crater on Phobos, or partially burying it in regolith, would allow additional shielding. Thus, using Phobos as a base would improve the radiation protection for the astronauts during the portion of the mission when they are in orbit around Mars.

However, Phobos also has considerable disadvantages for a teleoperation base. Although Phobos is not as difficult to land on as the surface of Mars itself, nevertheless the concept of landing a base on Phobos would increase the complexity of the mission. The equatorial orbit of Phobos means that without a relay satellite, sites to be explored would be restricted to only low latitude sites, although many sites of scientific interest are at high latitudes. The 459 minute period of Phobos means that even an equatorial site on the surface would only be in direct line of sight for a period of slightly over four hours, which is a short duration for a teleoperation shift. Finally, and most important, the delta-V required for reaching (and leaving) Phobos orbit is larger than that for reaching the highly elliptical Mars orbit baselined. This higher delta-V substantially raises the fuel use, and hence increases the mission cost.

For these reasons, Phobos was not selected as a base for teleoperation on Mars, although it, as well as Deimos, are attractive targets for future HERRO style missions as science targets in their own right.

V. HERRO-Venus Mission

Conducting one or more HERRO missions to Venus is predicated on the availability of a CTCV, whose capability is extensible to other destinations with comparable mission velocity requirements. It is assumed that HERRO-Venus would take place only as a follow-on to one or more HERRO-Mars missions,[5] which are assumed to occur during the 2030s. HERRO-Venus would follow a nearer-term robotic mission to the surface comparable to the proposed Venus "Flagship" mission,[20] which could occur between 2025 and 2040. Thus, it is reasonable to assume that a HERRO-Venus mission could occur as early as 2040, following a successful HERRO-Mars campaign.[6]

Scientific interest in Venus ranges from the highest levels of the atmosphere to the planet interior (*e.g.*, the cloud level, low altitudes below the clouds, the surface and subsurface). There have been proposed science missions involving orbiters, high-altitude balloons,[20] low-altitude balloons,[21,22] solar-powered aircraft,[23] airships,[24] landed surface missions,[20] rovers,[25] and sample return rockets.[22] Each of these mission concepts would investigate different portions of the total spectrum of Venus science.

Although an ideal mission would employ an assortment of probes to investigate a number of different altitudes, HERRO-Venus focuses on surface elements for which human telerobotic operation would be valuable. While atmospheric operations by balloon or aircraft would produce interesting science, it is assumed that these could be done by autonomous robots, and hence did not need to be incorporated into this mission.

The capabilities of the telerobots for this mission will depend on the assumptions of the technology. The choice of technologies capable of high temperature, high pressure operation will very likely improve by the time that this mission takes place. The baseline assumption is that all required technologies should have at least passed proof-of-concept or have been shown to operate in a laboratory environment. In terms of the Technology Readiness Level (TRL) scale, this corresponds to a minimum TRL of 3.

HERRO-Venus employs a CTCV design based on the HERRO-Mars CTCV, but modified for operation in the Venus orbit thermal environment, which is closer to the Sun and incurs greater planet albedo heating. The assumption is to reuse the HERRO Mars CTCV,[5] recovered from parking orbit at the Earth-Moon Lagrange (L1) point, which will be refurbished and refueled for the Venus Mission.

The goal of the HERRO-Venus mission is to achieve a level of scientific exploration comparable to that of HERRO-Mars in terms of number of sites explored and the quality of science gleaned at each site. Surface elements include four pairs of rovers positioned at four sites dispersed across the northern hemisphere of Venus. Each pair works cooperatively and is launched separately on an Atlas-V or Delta-IV. Another element that could be included is a sample-return system to bring selected rock and soil samples back to the CTCV, but such a capability was not considered in this study.

Each rover pair lands in a science location with the ability to traverse approximately a 100-kilometer diameter area over the course of the mission. The approach of splitting robotic functions in an arrangement similar to the Truck and Rockhounds was considered, but was deemed as too challenging and risky for communications relays and autonomous operations needed for energy replenishment.

The HERRO-Venus mission begins in December 2039 with launch and deployment of the four telerobotic pairs. Each transit to Venus lasts about 180 days, but it is assumed that the entire launch and landing of rover groups would take place over a year. These groups land using proven entry, descent and landing techniques at four different locations in the northern hemisphere of the planet.

After these groups are checked out and operational, the CTCV, which has been replenished with propellant and crew over a period of 80 to 90 days, departs Earth and follows a Hohman-class trajectory to Venus. An Earth escape

date of 21 December 2040 is assumed, thus yielding a 136-day transit to Venus. Once the CTCV captures into a highly elliptical 24-hr 180 degree orbit, it beings to spin at 2.7 rpm to provide Mars g-level artificial gravity. After the astronauts have acclimatized, they begin to operate the rovers.

The mission entails 472 days in Venus orbit. Once the surface exploration phase of the mission is finished, the CTVC despins and begins the 116-day return to Earth using an NTR burn. Final return of the crew is performed using the Orion vehicle on a hyperbolic trajectory. After the Orion vehicle has been jettisoned, the CTCV flies by Earth. Sufficient ΔV reserves are kept to return the CTCV to Earth-Moon L1, where it can be stored and refueled for use in future missions. The crewed part of HERRO-Venus is 724 days in duration, 176 days shorter than HERRO-Mars or DRA 5.0.

A. HERRO-Venus Orbit

Venus is unique among the planets of the solar system for its extremely slow rotation (sidereal day of 243 Earth days, retrograde). The slow rotation leads to very little equatorial bulge, which means that orbital precession rates for Venus are extremely slow. Compared to orbits about Earth, orbits around Venus remain comparatively fixed in inertial space.

The mission concept assumes Hohmann launch windows, with a 472-day stay in Venus orbit before the launch window for the Earth return. This period is longer than both the Venus sidereal day and the Venus year (224.7 Earth days). Thus, the planet will rotate under the plane of the CTCV's orbit, and the orientation of the orbit to the sun will be changing. The mission is also longer than the Venus solar day (117 Earth days). Therefore, any surface site will experience both day (illuminated) and night (dark) periods. The study assumes that telerobotic science is performed primarily during the day periods, but driving is possible during the night at a relatively low speed of 120 meters/hour per 8-hour drive shift.

Similar to HERRO-Mars,[5] communications between the CTCV and the ground science sites could be done by either a direct link or use of one or more communications satellite relays. The communications relay option increases the flexibility of the choice of orbits, but has the disadvantage of greater complexity, added failure modes, and a larger number of elements. Hence, the baseline is a CTCV orbit that provides a direct view of the surface as much as possible during telerobotic operations.

The orbital requirement is for a minimum of 8 hours of coverage per operational shift each day at each operations site, and for operation at two illuminated (daytime) sites during the full mission, dispersed around the globe. Furthermore, it is required that the real-time round-trip communications delay between crew and landers be <1 second (and preferably under ~200 ms).[15]

The orbital options considered include: 24-hr circular orbit; Lagrange point (Sun-Venus L1) halo orbit; high-elliptic equatorial 24-hr orbit; high-elliptic, equatorial 24-hr orbit with propulsive precession of the orbit; and high-elliptic 24-hr polar orbit (apoapsis above pole). The 24-hr circular orbit was eliminated because it had an unacceptably high cost in terms of injection and departure ΔV. The L1 halo orbit was eliminated because it had too long of a speed-of-light delay to allow acceptable real time control. Because of low precession of orbits around Venus, the highly-eccentric equatorial orbit remains nearly fixed in inertial space, and hence would have 58 days with the apoapsis above the sunlit hemisphere of Venus, followed by 58 days above the night hemisphere.

The option to precess the orbit propulsively was examined, but a 1 deg change in argument of periapsis required 67 m/s of delta-v, roughly equal to 4,453 kg of propellant. The propellant required to precess the orbit to maintain the apoapsis in sunlight was thus excessive, and that option was also eliminated. Thus, orbit selected was a highly-elliptical 24 hour polar orbit, chosen with the apoapsis over the pole of the planet. The resulting 39,457-km semimajor axis leads to a maximum speed of light delay in operations of about 220 ms, similar to Earth geosynchronous time delay, which is at the high end of the acceptable value for teleoperation.[15]

B. HERRO-Venus Surface Operations

The surface operations for HERRO-Venus are different than those for HERRO-Mars. Rovers are landed in four regions in the northern hemisphere (spaced roughly 90° apart), and the crew explores two regions simultaneously (sunlit). Figure 7 shows how these regions are decomposed into science sites, which represent the endpoints for gross movement and transport for the robot pair in that region.

The pace of operations is set by the Venus solar day. Each site is in daylight for approximately 58 Earth days; and then is in darkness for an equal period. The duration of telerobotic science activity is restricted to the daylight period. During this period, the orbital crew uses the rovers to explore a science region. Within each science region, they will be able to perform detailed investigations at many individual science sites. At the end of daylight operations, the rovers will move on to a new science site, which could be up to 50 km distant.

Several methods were considered for relocation to new science locations, including use of a separate "Truck" vehicles designed for long-distance transport, use of high-temperature "bellows" balloons,[22] and even transport via a "land-sail" vehicle that would be propelled by slow, dense surface winds.

Given the long duration of time allowed for transportation (set by the long Venus night), a simpler and more controlled relocation

Figure 7. HERRO-Venus exploration areas.

option turned out to be just using the rover drive capability. Even at a very conservative drive speed of 0.11 km/hour (3 cm/sec) during the 8-hour drive shift (yielding an average speed 1 cm/sec), a drive of up to 50 km could be done in the allowed time. Driving during the night assumes that the rover drivers have a pre-defined route, using detailed maps made from radar or infrared imaging of the surface, which allows avoidance of major obstacles. As well as incorporating a radar reflector, the rovers will also incorporate headlights, in order for smaller scale obstacles to be seen and avoided.
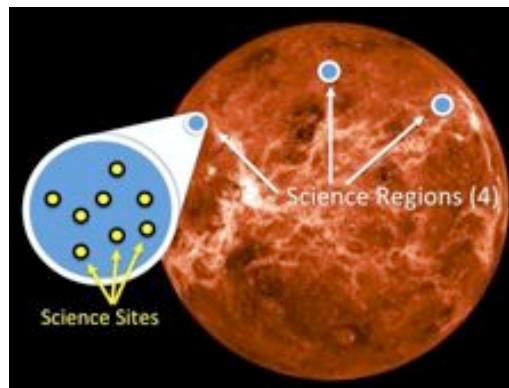
C. HERRO-Venus Surface Rover

The robotic rover in this study approximates that from an earlier study of Venus surface exploration sponsored by the NASA Revolutionary Aerospace Systems Concepts (RASC) program.[10] The most significant design challenge for the Venus rover is the high temperature of the atmosphere at the surface. Another important consideration is the surface pressure of 92 bars, which not only presents design complications, but also complicates the thermal design of the rover.

To accommodate a range of landing sites, the rover design is specified to operate at a maximum external temperature of 500°C. Although some electronics currently exist which could operate at this temperature, not all the functions required of the rover can be designed with existing electronics. Therefore, the design assumes a cooled electronics enclosure in which the heat-sensitive electronics are located. To the maximum extent possible, components are used which can be designed to tolerate the Venus ambient temperature, and hence can be located outside this electronics enclosure, in order to minimize the internal heat generated.
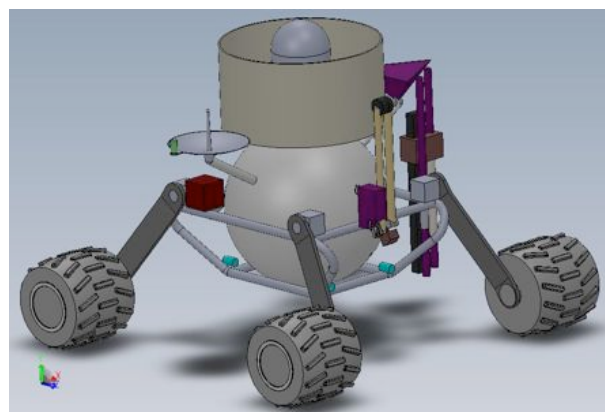

Figure 8. Venus Rover.

To minimize external heat flow into the electronics enclosure (and also to provide structural strength against external pressure), the electronics enclosure is assumed to be spherical shell, with a minimum amount of thermal penetrations. Figure 8 shows an illustration of the rover design. The dimension from the front wheel axle to the rear is 2.0 m.

Planetary entry is performed using a direct atmospheric entry, following the model of the Pioneer Venus mission atmospheric probes. The HERRO rovers use a 4.5-meter diameter aeroshell based on the Pioneer-Venus design.

Figure 9 shows one of the Venus rovers packed in the aeroshell. After atmospheric entry and deceleration, the heat shield is dropped and the vehicle is slowed by deployment of a drogue parachute, followed by a second, high-temperature parachute.
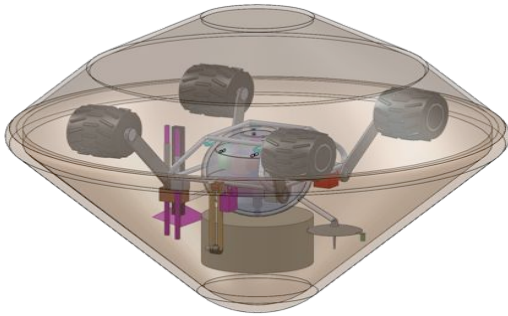
VI. Conclusions

Figure 9. Venus rover inside 4.5-meter diameter Atmospheric entry aeroshell

Concepts for human missions to the orbits of Mars and Venus were presented. The concepts utilize the same CTCV planetary transfer spacecraft and feature the use surface exploration via telerobotics operated by the crew in orbit. Although no cost estimates were derived for these mission concepts, it is readily apparent that both could be implemented with substantially less infrastructure than human Mars surface missions.

There are several advantages in considering telerobotic surface exploration for human spaceflight. First, it expands the spectrum of missions by opening up a new world for intensive, robot-facilitated human exploration. In addition it offers a synergistic human/robotic approach to the study of scientifically rich planets by eliminating speed-of-light delay, increasing effective data and command rates over autonomous robotic missions. In the case of Venus, it also permits use of longer-lived robotic elements on the surface through use of simple, high-temperature computational electronics, and allows exploration with human telepresence.

Future work will focus on more refined designs for the CTCV and the telerobotic surface elements. It would also be desirable to develop cost estimates for these mission concepts and compare them with those for more conventional exploration missions.

VII. References

1. Schmidt, G. R., Oleson, S. R., Borowski, S. K., and Landis, G. A., "HERRO: A Science-Oriented Strategy for Crewed Missions Beyond LEO," AIAA-2010-0629, *AIAA Aerospace Sciences Conference*, January 6-9 2010, Orlando, FL.
2. Schmidt, G. R., Landis, G. A., and Oleson, S. R., Rational for Flexible Path - A Space Exploration Strategy for the 21st Century, *Journal of the British Interplanetary Society,* Vol. 63, pp. 42-52, 2010
3. Landis, G. A., "Teleoperation From Mars Orbit: A Proposal for Human Exploration," paper IAC−04−IAA.3.7.2.05, *Acta Astronautica, Vol. 62.1*, pp. 59-65, January 2008.
4. Landis, G. A., "Footsteps to Mars: an Incremental Approach to Mars Exploration," *Journal of the British Interplanetary Society*, Vol. 48, pp. 367-342, 1995. Presented at Case for Mars V, Boulder CO, 26-29 May 1993.
5. Oleson, S. R., Landis, G. A., McGuire, M. L., and Schmidt, G. R., "HERRO-Mars: Design Study for a Highly-Robotic Human Mission to Mars," AIAA-2011-0334, *AIAA Aerospace Sciences Meeting*, January 4-7, 2011, Orlando FL.
6. Landis, G., Dyson, R., McGuire, M., Oleson, S., Schmidt, G., Grantier, J., Burke, L., Dux, I., Bur, M., Fincannon, J., Bury, K., Mongalier, M., Williams, G., Warner, J., Packard, T., Colozza, A., Martini, M., Fittje, J., Schmitz, P., Gyekenyesi, J., and McCurdy, D., "Human Telerobotic Exploration of Venus: A Flexible Path Design Study," AIAA-2011-0335, *AIAA Aerospace Sciences Meeting*, January 4-7, 2011, Orlando FL.
7. Feldman, M.S., Ferrara, L.A., P.L., Havenstein, J.E., Volonte, and Whippie, P.H., "Manned Venus Flyby," Belcomm, Inc., TR-67-600-1-1, Performed for NASA Manned Space Flight Center under Contract NASw-417, Feb 1, 1967.
8. Hunter, G.W., Neudeck, P.G., Okojie, R.S.,. Beheim, G. M, Kraskowski, M., Ponchak, G.E. and Chen, L.-Y., "High Temperature Electronics, Communications, and Supporting Technologies for Venus Missions," 5th International Planetary Probe Workshop, IPPW-5, Bordeaux, France June 23-29 2007.
9. Dyson, R.W., Schmitz, F.G., Penswick, L.B., and Bruder, G.A., "Long-Lived Venus Lander Conceptual Design: How To Keep It Cool," paper AIAA-2009-4631, 7th International Energy Conversion Engineering Conference, Denver CO, August 2-5 2009.
10. Drake, B. G., *Human Exploration of Mars Design Reference Architecture 5.0,* Lyndon B. Johnson Space Center, February 2009

11. Borowski, S.K.; McCurdy, D.R.; and Packard, T.W., "Nuclear Thermal Rocket/Vehicle Characteristics and Sensitivity Trades for NASA's Mars Design Reference Architecture (DRA) 5.0 Study," paper 203599, *Nuclear and Emerging Technologies for Space 2009*, Atlanta, GA, June 2009.

12. COMPASS Team, NASA Glenn Research Center (team lead S. R. Oleson), COMPASS Final: Human Exploration Using Real-Time Robotic Operations (HERRO) - Crew Telerobotic Control Vehicle (CTCV) Design, report CD-2009-36, September 2009.

13. COMPASS Team, NASA Glenn Research Center (team lead S. R. Oleson), *COMPASS Final: Human Exploration Using Real-Time Robotic Operations (HERRO) - Truck Design*, report CD-2009-35, September 2009.

14. COMPASS Team, NASA Glenn Research Center (team lead S. R. Oleson), *COMPASS Final: Human Exploration Using Real-Time Robotic Operations (HERRO) - Rockhound Design*, report CD-2009-34, September 2009.

15. Lester, D., and Thronson, H., "Human Space Exploration and Human Space Flight: Latency and the Cognitive Scale of the Universe," *Space Policy, Vol. 27,* No. 2, pp. 89-93 (May 2011)..

16. Quinn, R.D., Kinglsey, D.A., Offi, J.T., and Ritzmann, R.E., "Improved Mobility Through Abstracted Biological Principles," *IEEE Int. Conf. On Intelligent Robots and Systems (IROS'02)* Lausanne, Switzerland (2002).

17. Schroer, R.T., Boggess, M.J., Bachmann, R.J., Quinn, R.D., and Ritzmann, R.E., "Comparing Cockroach and Whegs robot body motions," *Proceedings of ICRA '04, the 2004 IEEE International Conference on Robotics and Automation, Vol.4*, April 26-May 1, 2004, pp. 3288 - 3293. doi: 10.1109/ROBOT.2004.1308761

18. Ambrose, R. O., Aldridge, H., Askew, R. S., Burridge, R. R., Bluethmann, W., Diftler, M., Lovchik, C., Magruder, D., and Rehnmark, F., "Robonaut: NASA's Space Humanoid," *IEEE Intelligent Systems,* July-Aug 2000, pp. 57-63.

19. Wettergreen, D., *et al*., "Developing Nomad for Robotic Exploration of the Atacama Desert," *Robotics and Autonomous Systems, Vol. 26,* no. 2−3, Feb. 1999, pp. 127−148.

20. NASA, Venus Science and Technology Definition Team, *Venus Flagship Study Report: Final Report of the Venus Science and Technology Definition Team*, JPL, April 17, 2009.

21. Landis, G. A., "Low-altitude Exploration of the Venus Atmosphere by Balloon," paper 2010-628, *48th AIAA Aerospace Sciences Meeting*, Orlando FL, January 6-9 2010.

22 Kerzhanovich, V. V., Hall, J., Yavrouian, A., and Cutts, J., "Two Balloon System to Lift Payloads for the Surface of Venus," paper AIAA-2005-07322, *AIAA 5th ATIO and 16th Light-Than-Air Systems, Tech. and Balloon Systems Conferences*, Arlington VA, Sept 26-28, 2005; see also Lunar and Planetary Science XXXVI, abstract 1223 (2005).

23. Landis, G. A., LaMarre, C. M., and Colozza, A., "Atmospheric Flight on Venus: A Conceptual Design," *Journal of Spacecraft and Rockets, Vol. 40,* No. 5, Sept-Oct. 2003, pp. 672-677.

24. Colozza, A., *Airships for Planetary Exploration,* NASA CR-2004-213345, November 2004.

25. Landis, G.A., "Robotic Exploration of the Surface and Atmosphere of Venus," *Acta Astronautica, Vol. 59,* No. 7, October 2006, pp. 517-580.